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INVESTIGATION OF THE FLOW THROUGH A PERFORATED WALL

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PREFACE

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ABSTRACT

The flow through a perforated wall is investigated using a modified form of Tollmien's solution for a free jet. The results of experiments indicate that this type of flow is a mixing phenomenon, and that the Reynolds number is of secondary importance.

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SYMBOLS

A	Cross-sectional area of test section
b	Mixing width
c	Constant
d	Width of test section
h	Height " " "
ℓ	Mixing length
m	Mass of air
m'	Dimensionless form
Δm	Mass of air flowing out holes
r'	Hydraulic radius
u	Velocity in x-direction
u_∞	" of parallel flow
v	" in y-direction
x, y	Rectangular coordinates
α	Constant
α_0	"
ρ	Density of air
δ	Ratio of open area to total area

FIGURES

1. Flow through Divergent Perforated Walls

2. Value of α_o

3. Velocity Profiles for Wall A

4. Velocity Profiles for Wall B

5. Velocity Profiles for Wall C

6. Velocity Profiles for Wall D

7. Velocity Profiles for Wall E

8. Velocity Profiles for Wall F

9. Comparison of Flow through Different Perforated Walls

I. INTRODUCTION

When considering the flow inside a wind tunnel which employs perforated walls in the test section, it is important to know the mass of air flowing out through the holes.

First, it is assumed that the flow can be treated similarly to that of a free jet i.e., the phenomena of mixing occurs. Because some of the air is restricted by the presence of the perforated walls, certain modifications have to be made concerning the amount of mixing that takes place.

It is known (Ref. 1.) that the rate of increase of the mixing width b is

$$\frac{Db}{dt} = \frac{\ell}{b} \; u_{\infty} \tag{1}$$

where ℓ is the mixing length and u_{∞} the free stream velocity. ℓ/b is a constant in any given case, but has different numerical values in other cases.

This seems to indicate that, although the relation between the velocity u and x which is the distance along the mixing region are unknown, the momentum at each section must be the same. Thus the momentum M is given by the relation

$$M = \text{number} \cdot \rho u_{\infty}^{2} b^{2} \tag{2}$$

and substituting in equation (1)

$$\frac{Db}{dt} = \text{number} \cdot u_{\infty} \frac{db}{dx}$$

or

$$\frac{db}{dx} = \text{number}$$

on integrating

$$b = \text{number} \cdot x + \text{constant} \tag{3}$$

The mixing length can be written proportional to b as

$$\ell_o = cx \tag{4}$$

The effect of the presence of the perforated walls makes it necessary to introduce another constant σ which is the ratio of the open area to the total area of the wall. Let us assume that the mixing length ℓ shall be proportional to the open length only and thus we obtain:

$$\ell = \sigma \ell_o = \sigma c \cdot x \tag{5}$$

However, there is no change in the boundary conditions between this case and that of an open jet, since it is assumed that the introduction of perforated walls has no effect on the flow at the boundaries.

The quantity of air flowing out through the holes can then be found by applying the continuity equation.

II. THEORY

When a parallel stream of air emerges from a wind tunnel of the open jet type it mixes with the surrounding air. Modification of the amount of mixing that occurs can be attained by introducing perforated walls in the test area of the wind tunnel. The exact solution for the case of the open jet has been found by W. Tollmien and is shown in some detail in Ref. 1. The solution for the perforated walls requires the following modifications:

1. The mixing length ℓ, which is proportional to the width b, is written $\ell = c\sigma x$, where c is the constant of proportionality and σ is the ratio of the open area to the total area.

2. There is a new $\alpha = c^{-2/3}\alpha_o$, where $\alpha_o = C^{-2/3}$ since α is proportional to the minus 2/3 power of the mixing length.

The quantity η which is proportional to y/b remains $\eta = y/x$.

Using the solution

$$F = C_1 e^{-\alpha\eta} + C_2 e^{\alpha\eta/2} \cos \frac{\sqrt{3}}{2}\alpha\eta + C_3 e^{\alpha\eta/2} \sin \frac{\sqrt{3}}{2}\alpha\eta \tag{6}$$

of the differential equation

$$FF'' + c^2 F''F''' = 0, \tag{7}$$

which satisfies the same boundary conditions as for free flow, namely:

1. $u = u_\infty$ and $v = 0$ at the boundary between the mixing zone and the flow in the test area, and $\frac{\partial u}{\partial y} = 0$ because of the continuous transition of velocity profiles. If the boundary is denoted by η_1, the conditions are expressed $F'(\eta_1) = 1$, $F(\eta_1) = \eta_1$ and $F''(\eta_1) = 0$
2. $u = 0$ and $\frac{\partial u}{\partial y} = 0$ at the boundary of the mixing zone and undisturbed air. These conditions can be denoted by η_2, so $F'(\eta_2) = 0$ and $F''(\eta_2) = 0$.

The solutions for the five unknowns C_1, C_2, C_3, η_1 and η_2 of equation (6) have been calculated and the values found to be

$\alpha C_1 = -0.0165$

$\alpha C_2 = 0.1374$

$\alpha C_3 = 0.6918$

$\alpha \eta_1 = 0.981$

$\alpha \eta_2 = -2.04$

where $\alpha_o = 11.8$.

Returning to the basic assumption that $u = u_{\infty} f(\eta)$ where $f(\eta)$ varies from zero in undisturbed air to the value one in the undisturbed parallel stream. Using the conditions of continuity and introducing a stream function, the velocities u and v were found as

$$u = u_{\infty} F'(\eta) \quad \text{and} \quad v = u\left(\eta F'(\eta) - F(\eta)\right).$$

It follows directly from the continuity equation that the mass of air Δm flowing out of the holes is

$$\Delta m = x \int_0^{-\eta_1} (\rho u_{\infty} - \rho u)\, d\eta \tag{8}$$

on integrating $\quad \Delta m = x \rho u_{\infty} \left(\eta_1 - F(\eta_1) + F(0)\right)$

and $\quad F(\eta_1) = \eta_1$

so $\quad \Delta m = x \rho u_{\infty} F(0)$

$$\Delta m = 0.1209\, x \rho u_{\infty} \frac{\sigma}{\alpha_0}^{2/3}$$

Reducing this result to dimensionless form, the equation becomes

$$m' = \frac{r'}{X} \frac{\Delta m}{m}$$

$$m' = \Delta m \frac{1}{x \rho u_{\infty}} \qquad m = \rho u_{\infty} A$$

thus $m' = 0.1209 \dfrac{\sigma^{2/3}}{\alpha_0} = 0.01023\, \sigma^{2/3}$ (9)

is the mass leaving an area of perforated wall equal to the tunnel cross sectional area divided by the mass going through the tunnel.

Also the mass flow can be calculated for the case where the perforated walls have a certain divergence. The amount of divergence is denoted $-\eta_3$.

The equation for the mass of air leaving is

$$\Delta m_1 = \int_0^{y_1} \rho u_\infty \, dy - \int_{y_3}^{y_1} \rho u \, dy \tag{10}$$

and expressing in terms of η

$$\Delta m_1 = x \rho u_\infty \left\{ \eta_1 - \int_{\eta_3}^{\eta_1} F'(\eta) \, d\eta \right\} \tag{11}$$

The boundary conditions remain the same as for the solution without divergence. Using the condition $F(\eta_1) = \eta_1$ equation (11) becomes

$$\Delta m = x \rho u_\infty F(\eta_3)$$

Reducing this to dimensionless form

$$m_1' = \frac{r'}{x} \frac{\Delta m_1}{m} = F(\eta_3)$$

and $$\alpha m_1' = \alpha F(\eta_3) \tag{12}$$

This result is shown in Fig. 1.

III. EXPERIMENTAL INVESTIGATION

A. Apparatus

A small wind tunnel operating at a constant velocity of 21.7 meters/second was used to obtain the data for this report. Two parallel walls formed the test section, which had a cross-section of 4" x 8". One side was open to give atmospheric conditions at the boundary. The fourth side provided a test area of 4" x 14" to which the perforated walls were attached. The boundary layer was removed as the flow emerged from the nozzle.

A Betz water manometer gave absolute pressure measurements within 0.1 mm of water. The velocity profiles were obtained using a single total head probe flattened to read a minimum 0.015 inches from the wall. A micrometer head was used to measure the distances from the wall into the velocity stream. Static pressure readings were made with a probe located at the centerline of the tunnel at each station.

B. Investigation for Porous Walls

1. Procedure

Pressure measurements were made for the open jet arrangement of the tunnel at stations three, six, nine, and twelve inches along the wall. This was done to compare the constant α_o of this setup with the value given in Ref. 1.

Perforated walls were fitted on the test area and pressure measurements and velocity profiles made for the same stations along the wall. The characteristics of the perforated walls were

Wall	dia. of hole (inches)	Holes/in^2	σ	α	arrangement of holes
A	.057	108	.276	25.35	hexagonal
B	.057	144	.367	21.49	square
C	.045	165	.260	27.02	hexagonal
D	.045	225	.370	21.37	square
E	.023	420	.196	32.65	hexagonal
F	.023	576	.250	27.74	square

2. Test Results

In the case of the open jet it was necessary to compare α_o for the particular arrangement with the known value. This was done in Fig. 2 where the correction has been made. For the results obtained α_o was reduced to 11.0 so the maximum number of points would fall close to the previous result.

In Figs. 3 through 8 velocity profiles for the six different perforated walls are shown. Using these profiles the mass of air leaving through the holes was determined by

$$\Delta m = \rho u_\infty d \int_0^\delta \left(1 - \frac{u}{u_\infty}\right) dy \tag{13}$$

or changing to dimensionless form

where $$m' = \frac{r'}{x} \cdot \frac{\Delta m}{m} \quad \text{and} \quad r' = \frac{A}{d} = h$$

and $$m = \rho u_\infty A$$

then $$m' = \int_0^\delta \left(1 - \frac{u}{u_\infty}\right) \frac{dy}{x}$$

and $$\alpha m' = \alpha \int_0^\delta \left(1 - \frac{u}{u_\infty}\right) \frac{dy}{x} \tag{14}$$

The values of m' for the different perforated walls at lengths x are

Wall	x	3"	6"	9"	12"
A	$\alpha m'$	.2931	.1674	.1510	.1505
B	$\alpha m'$	.2835	.2248	.2197	.2435
C	$\alpha m'$	.3025	.1928	.1501	.1270
D	$\alpha m'$	.2908	.2264	.2042	.1901
E	$\alpha m'$	.2785	.1480	.1016	.0849
F	$\alpha m'$	.3143	.1627	.1135	.1119

These results are shown in Fig. 9.

No measurements were made for the case of divergence, but the theoretical results are shown.

IV. CONCLUSIONS

The experimental results obtained for flow through perforated walls is in agreement with the original assumption - that this type of flow is a mixing phenomena. This is indicated in Fig. 9 where it is seen that the values of $\alpha m'$ at stations along the wall approach the theoretical value farther downstream.

There are also two indications that this phenomena is independent of the size of the tunnel, since the Reynolds number influence is negligible. The first is shown in the results plotted in Fig. 2 where, for flow from an open jet, the value of the coefficient α_0 is the same as for the results of the Göttingen tunnel as given in Ref. 1. By comparing the increase in the displacement thickness for particular perforated walls with results obtained by other persons conducting similar experiments (Ref. 2), it is seen that good agreement is obtained. In this comparison the difference in Reynolds number was quite large, but the influence was negligible.

Thus, in conclusion one may state that the flow through perforated walls should be treated as a mixing process and that the Reynolds number is of secondary importance.

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Ref. 2. Rice, Janet B.: Experiments with Various Nozzle and Porous Wall Configurations in Small-Scale Two Dimensional Transonic Tunnel., Progress Report for Contract AF 18(600)-17[illegible] E.O.R-465-BR-1.

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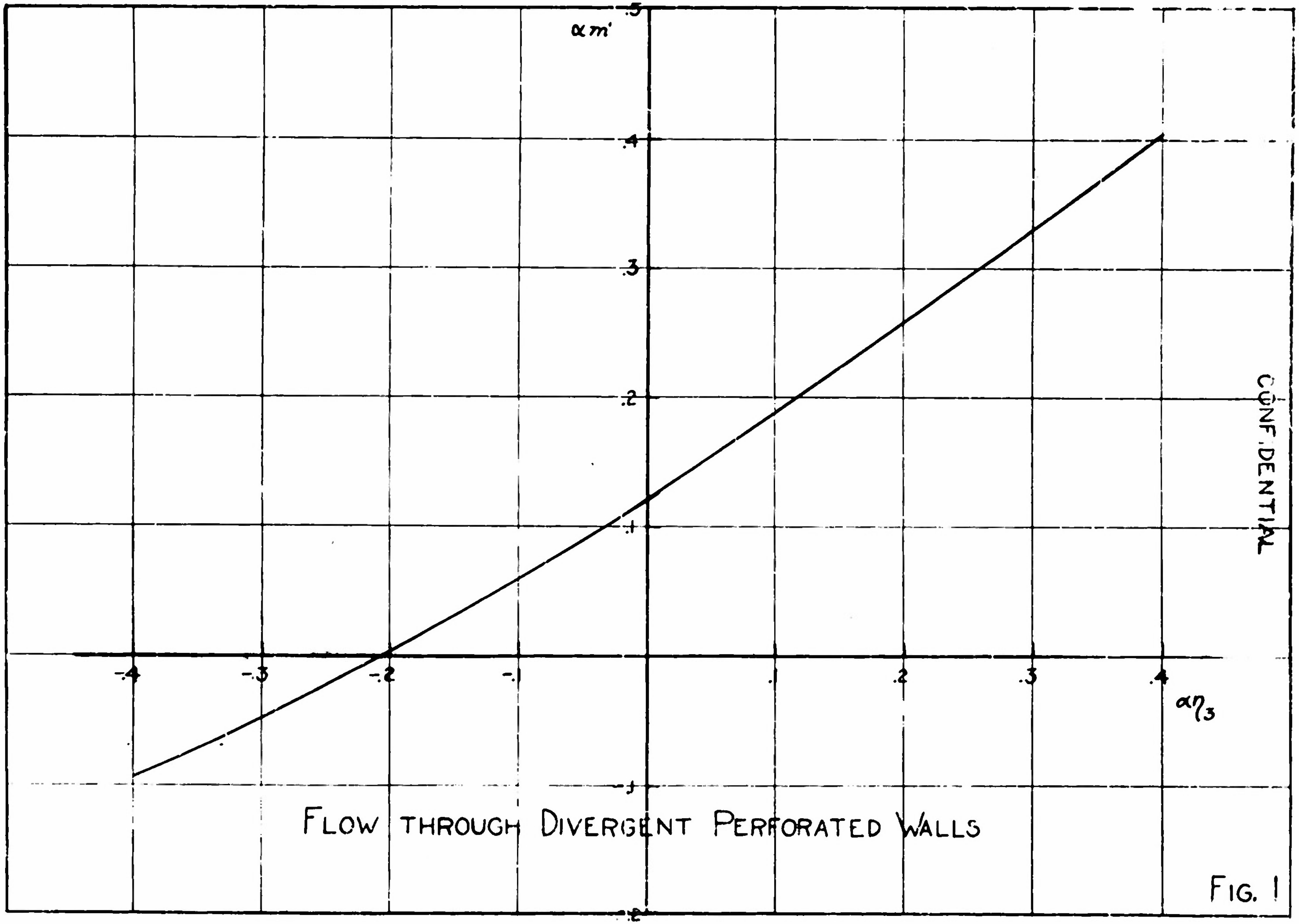

FLOW THROUGH DIVERGENT PERFORATED WALLS

FIG. 1

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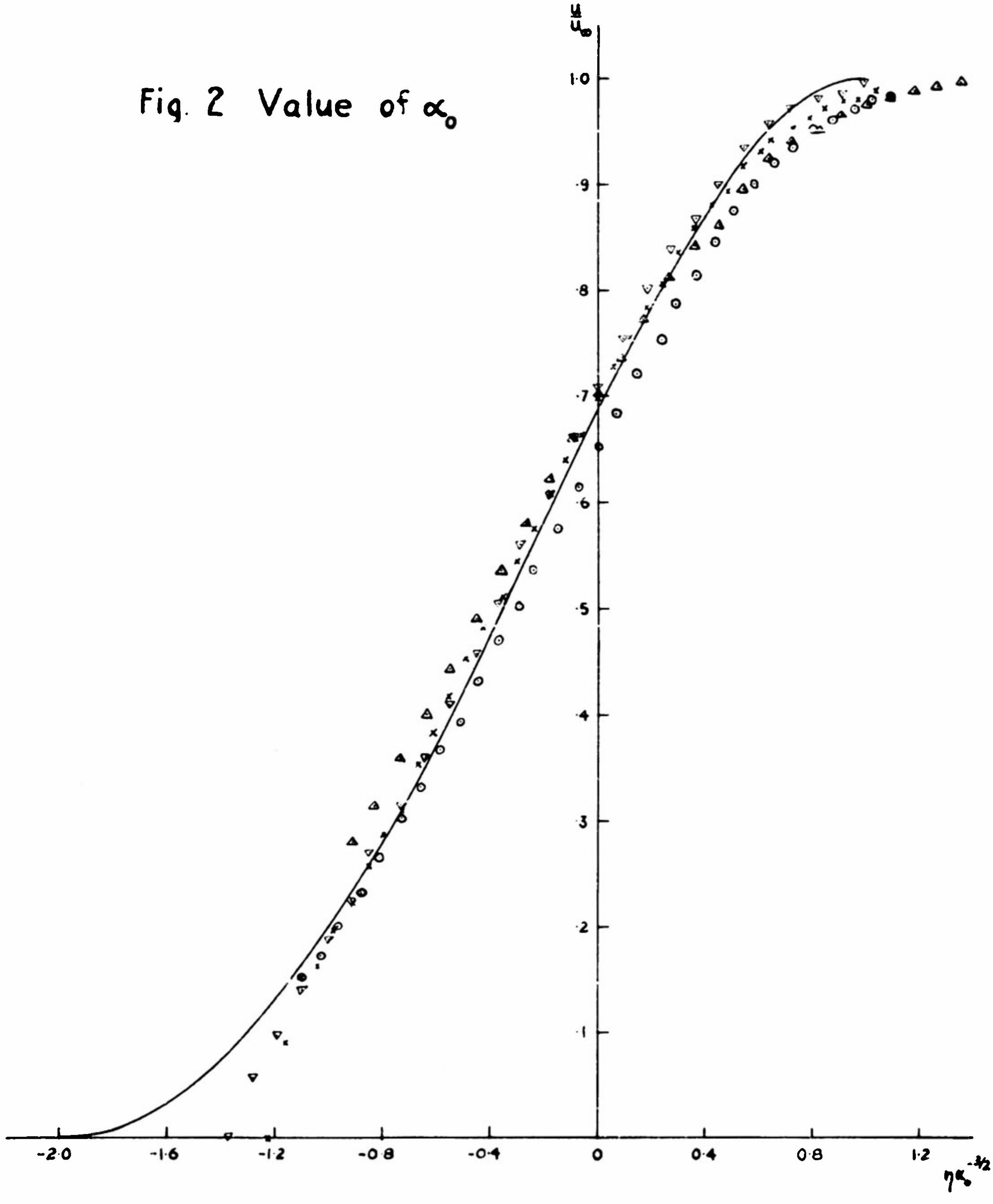
Fig. 2 Value of α_0



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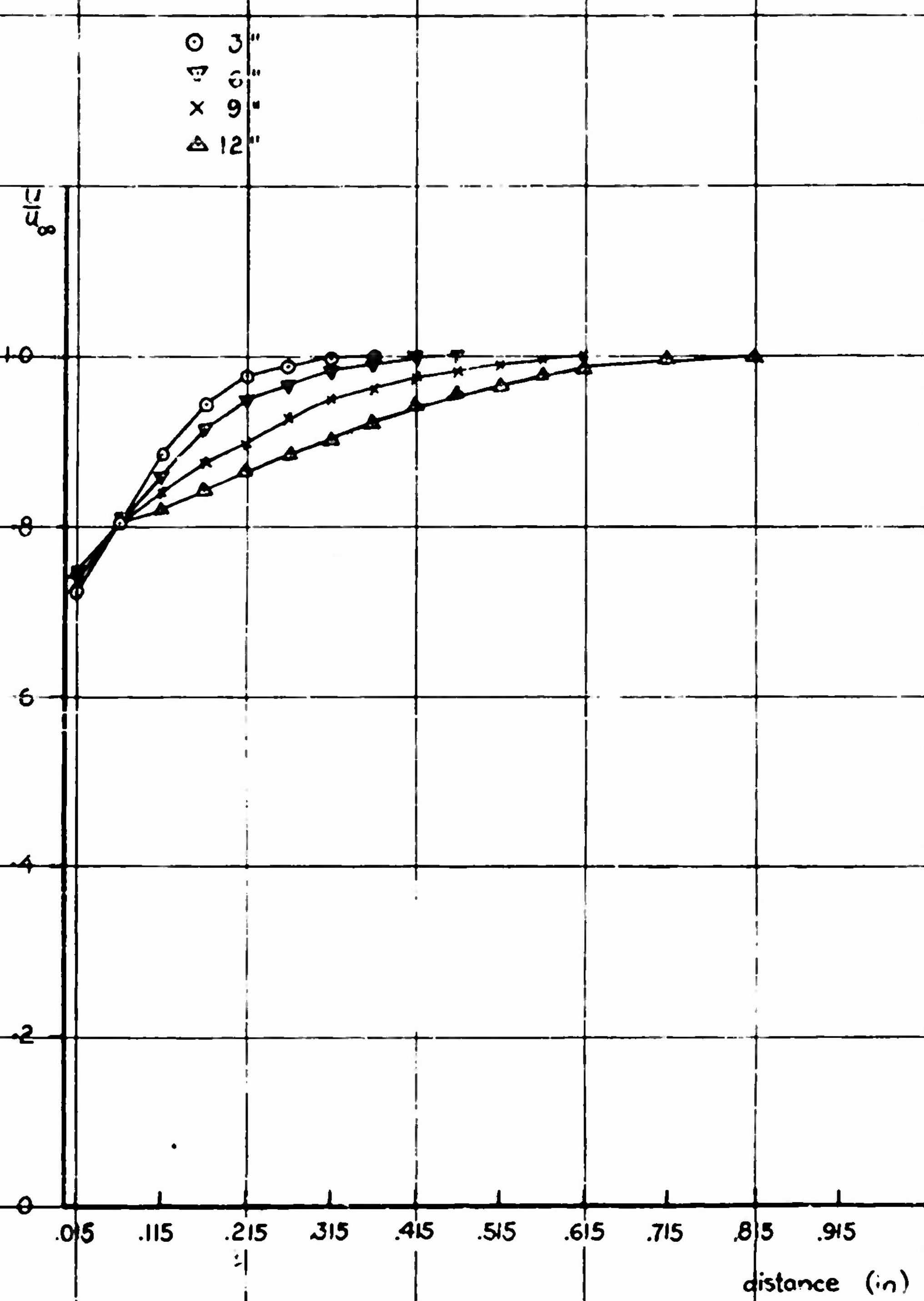

VELOCITY PROFILES FOR WALL A

FIG. 3

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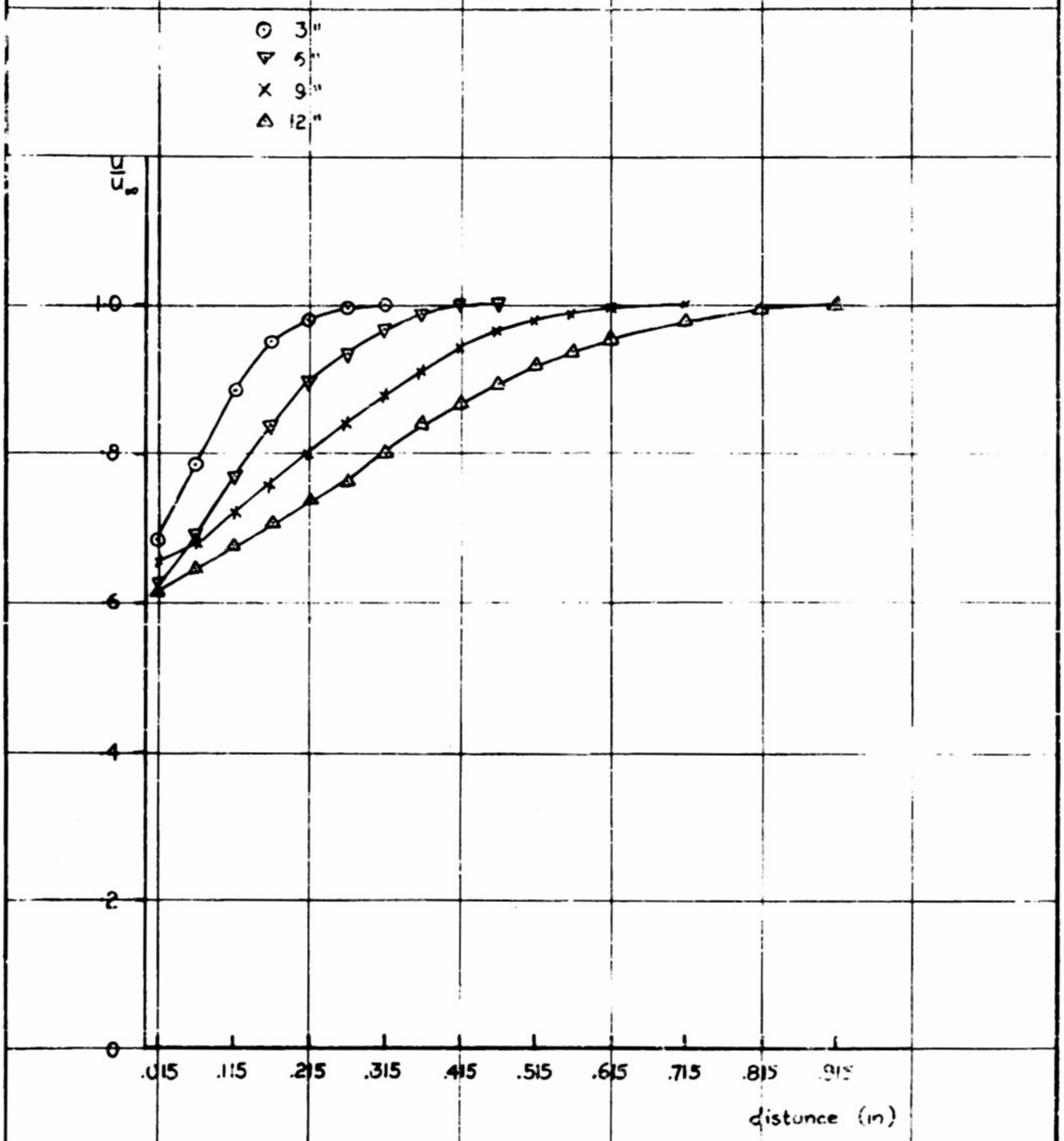

VELOCITY PROFILES FOR WALL B

FIG. 4

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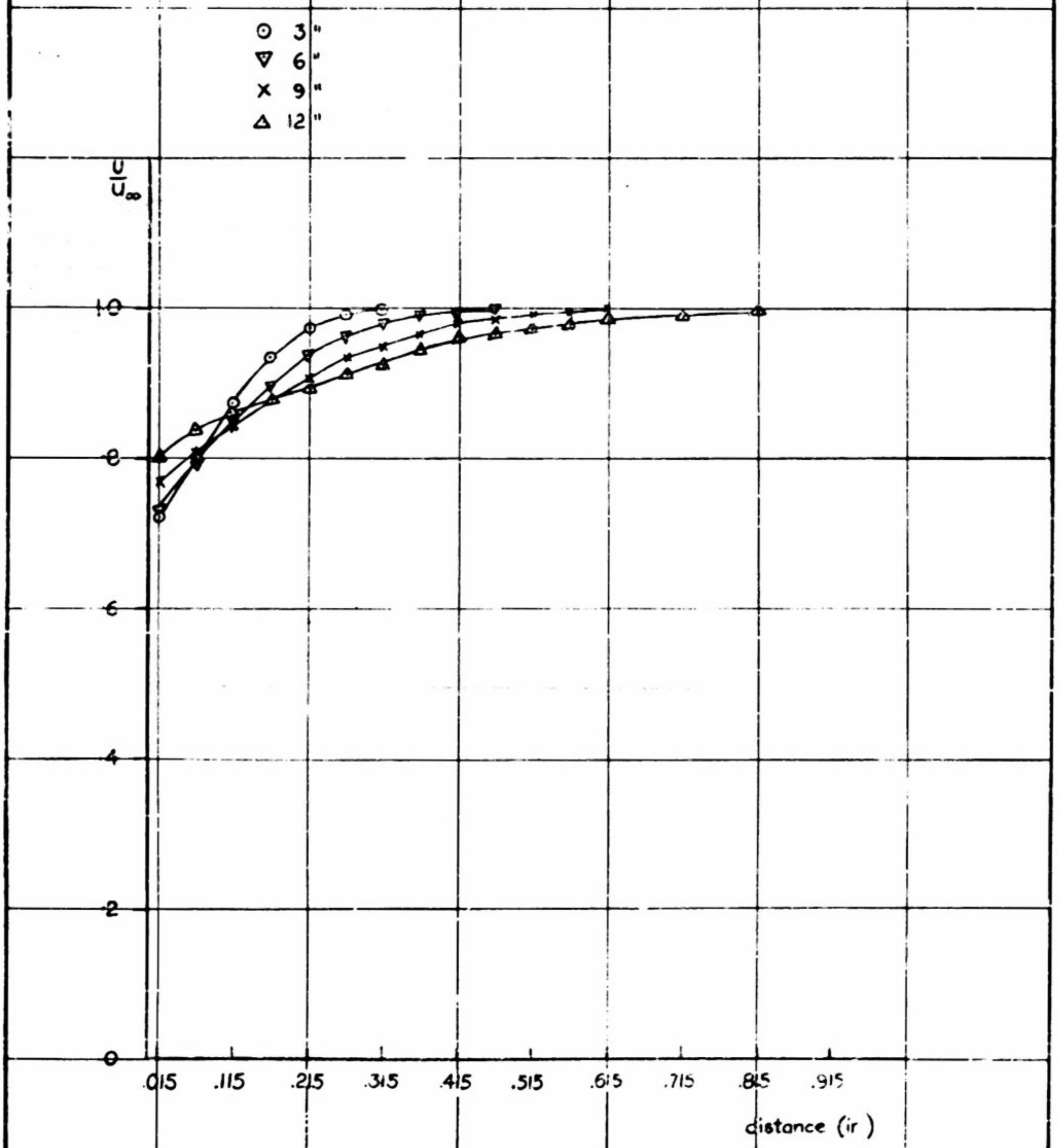

VELOCITY PROFILES FOR WALL C

FIG. 5

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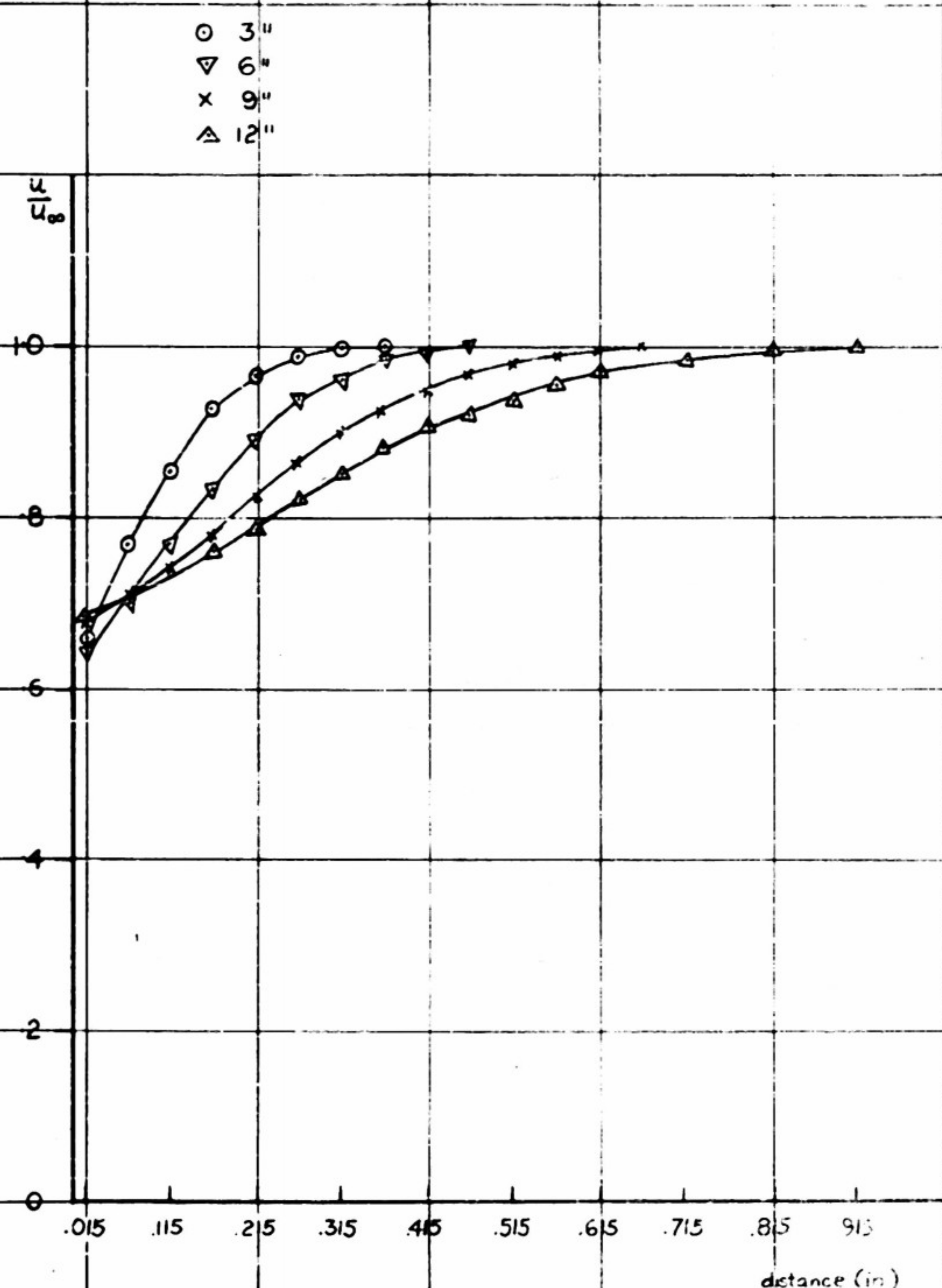
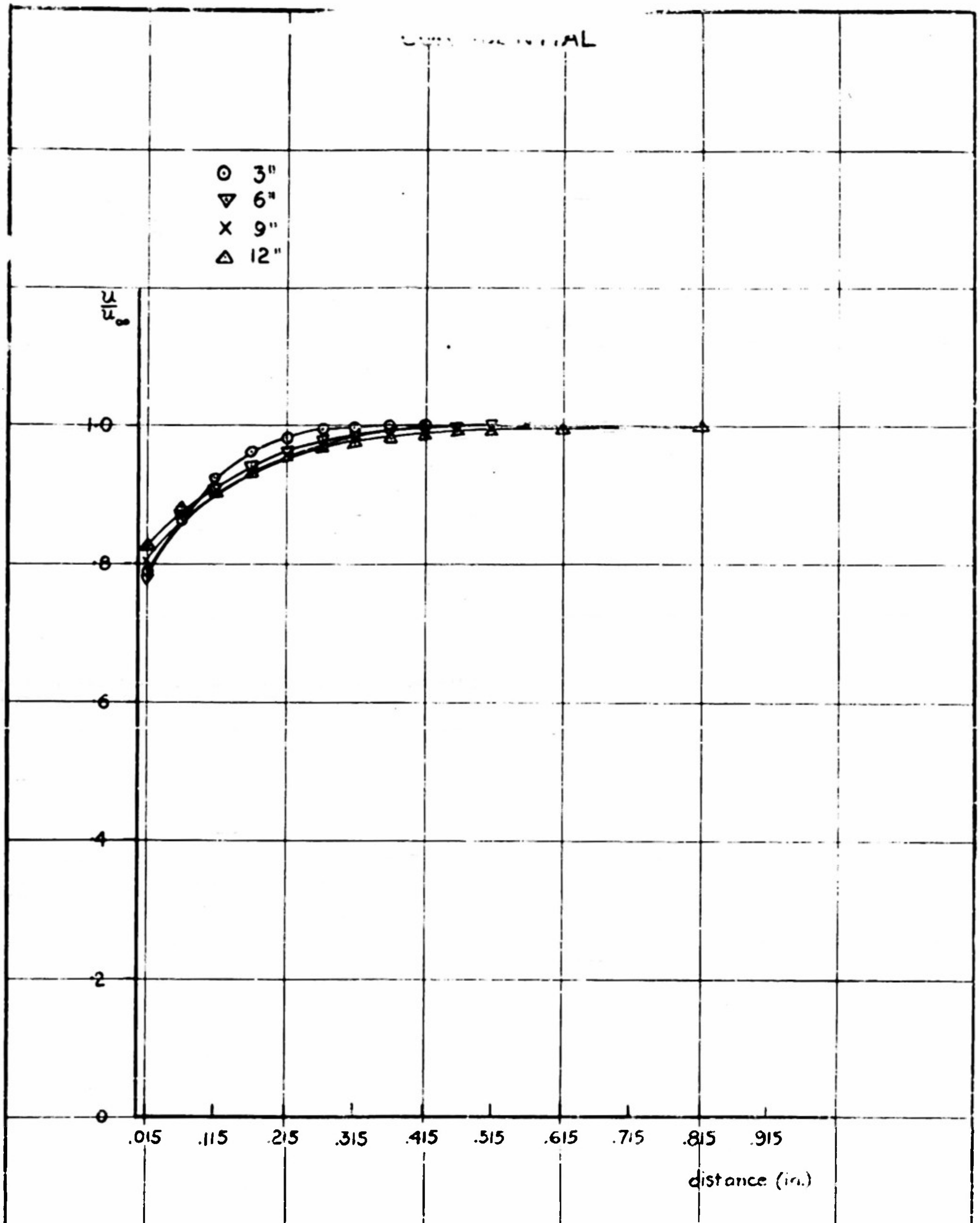


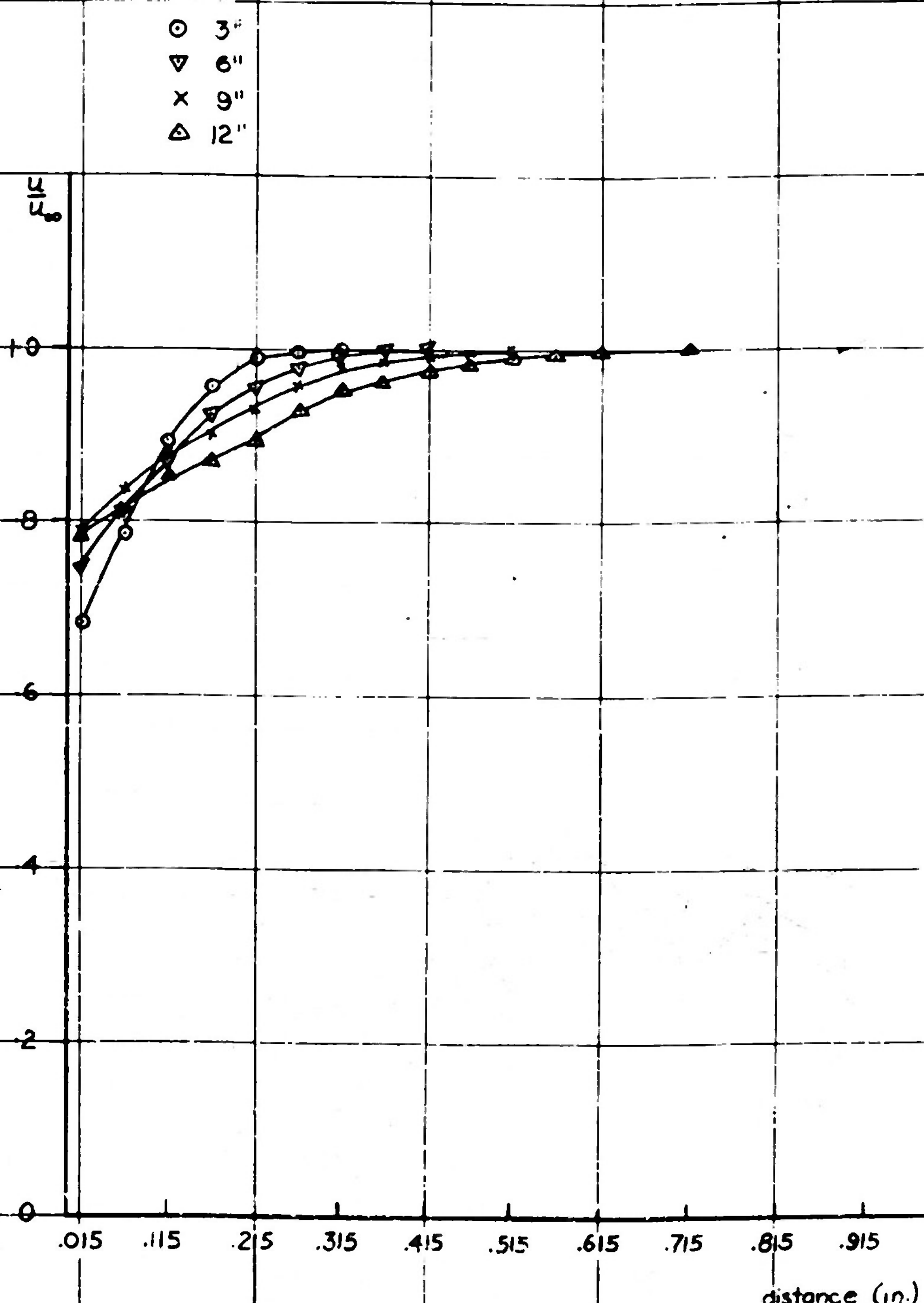
VELOCITY PROFILES FOR WALL D

FIG. 6



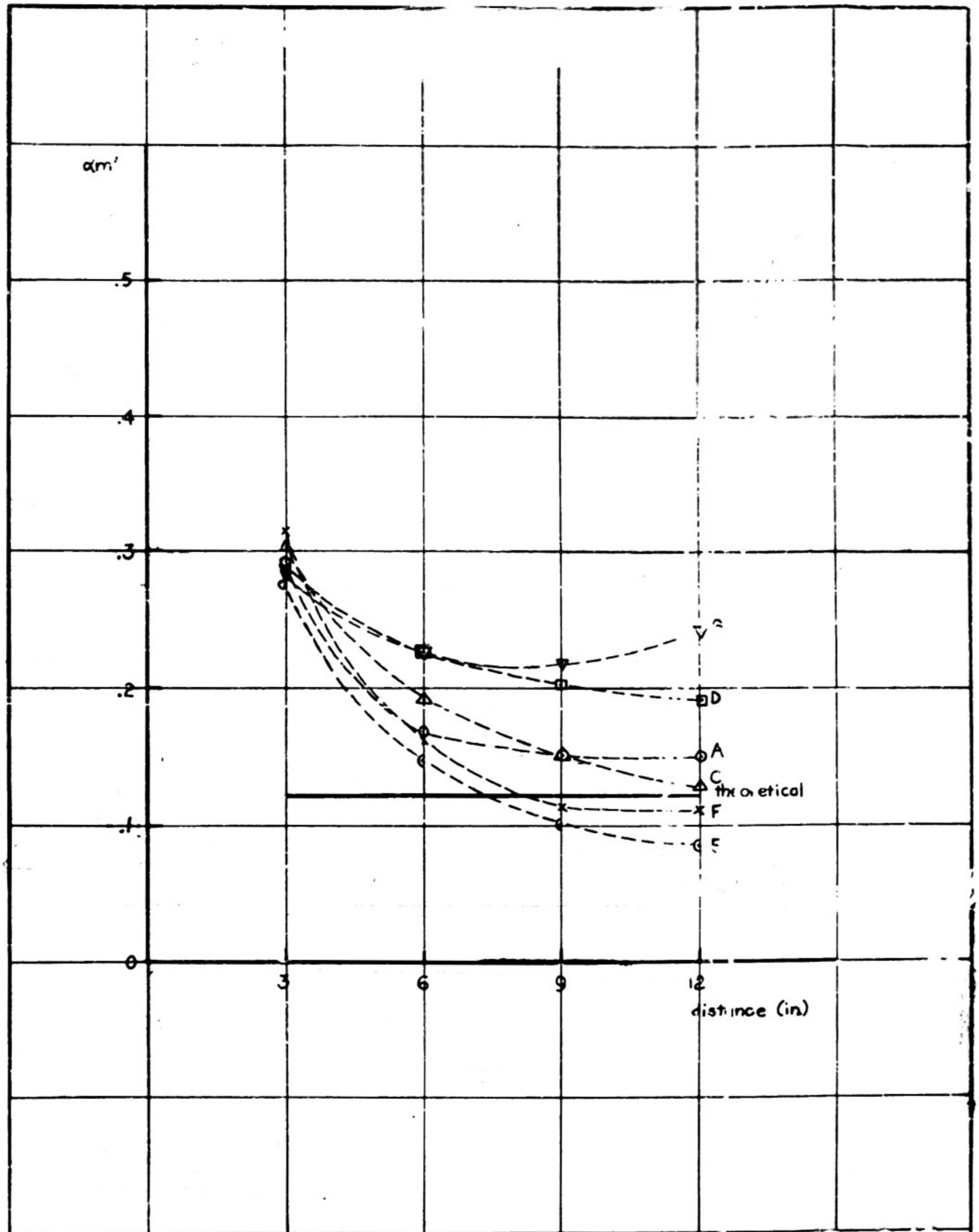
VELOCITY PROFILES FOR WALL E

FIG. 7



VELOCITY PROFILES FOR WALL F

FIG. 8



COMPARISON OF FLOW THROUGH DIFFERENT PERFORATED WALLS

FIG. 9